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High-Order Surface Gradient Coil Design Using Target Field Approach †

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= Abstract =

The purpose of this paper is to design high-order (or radial) surface gradient coil (SGC), which can provide multi-dimensional spatial selection. Although the spatial Selection with High-Order gradienT (SHOT) can provide a 2-D selection with only one selective RF pulse, the high-order gradient produced by conventional cylindrical-shape coils has not been clinically useful due to the large selection size caused by the limited radial gradient intensity. However, by using the proposed high-order SGCs located near the imaging region, the size of volume selection can be reduced to a clinically useful size of 1~2 cm in diameter by applying stronger radial gradient field with much less gradient driving power. So far radial SGCs have been designed by using the field component method and may cause distortion in the selection shapes. In this paper, by using the target field approach for the coil design, selected volumes became almost circular. A 40 cm-by-40 cm z^2-surface gradient coil has been designed and implemented by using the target field approach. Phantom and volunteer studies have been performed. Experimental results using spatially localized MRI show good agreement to the theoretically predicted behavior.

Key words : Target field approach, High-order (or Radial) gradient, Selection with High-Order gradienT (SHOT), Surface Gradient Coil (SGC).

INTRODUCTION

Since high-order magnetic field gradients can provide multi-dimensional selection with only one selective RF pulse (SHOT: Selection with High-Order GradienT), they are useful for spatial selection for localized volume spectroscopy or imaging[1,2]. By using a radial gradient field to select a volume in two directions or more, one can achieve a 3-dimensional selection with only one or two selective RF pulses which leads to many advantages in spatial localization for MRS and MRI, for example, shorter minimum echo time and less selection artifact. However, due to the necessity of too much driving power to generate proper gradient intensity, its application has been limited to small-bore animal systems[1,2] or, to the selection of unreasonably large volume in case of large-bore systems, which is clinically not useful[3]. To overcome this problem, the use of Surface Gradient Coils (SGC) designed using field component method has been proposed[4]. The advantages of using SHOT using SGCs are:

(1) A 3-D selection can be achieved by using only two selective RF pluses. After a dumb-bell-shaped volume is selected by a 90° excitation RF pulse applied with the radial gradient,

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the z-directional selection is performed by only one more selective RF pulse applied with a z-gradient (See Fig. 1 for a 3-D selection process.).

(2) Compared to the cylindrical r^2 gradient coil for a whole-body system where more than 130 Amp. (more than 10 kWatt of instantaneous power) was needed to select a 8-cm-diameter circular volume (radial direction selection)[5], 1 to 4-cm-diameter region can be selected with less gradient driving power (less than 10 Watt).

There are two methods in coil design, that is, the target field approach and the field component method[6,7]. In the target field approach[6], specific points are set to have specific field intensities, and in the field component method[7], a specific field component is set to a certain non-zero value, while other components to be removed are set to zero. For cylindrical gradient coil design, the field component method usually gives resonable result due to its symmetry[7]. In case of the surface gradient coil, however, due to the difficulties in choosing the field components for field optimization, selected volumes usually have distortions in the selection shapes. If the field pattern of the coil is simple, it is not difficult to choose the field components. However, if the field pattern is complicated as the case of high-order gradient, it is very difficult to choose the field components. To overcome this

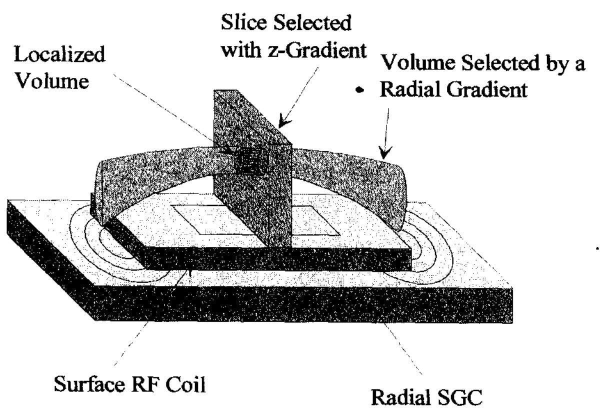


Fig. 1. 3-D selection process using the high-order (r^2) SGC. After a radial dumbbell-shaped volume is selected by applying a selective RF pulse with a radial gradient, the spins in the z directional slice are selectively refocused by a 180° selective RF pulse

problem, a better radial gradient surface coil design scheme using target field approach method is proposed in this paper. According to the simulation and experimental results, the field pattern produced by the designed coil appears to have an almost-ideal circular shape.

METHOD

The r^2 (or radial) SGC is designed by using the target field approach as follows:

(1) X-directional current elements of 400 positions on xz-plane covering the area of 40 cm × 40 cm square plane were selected for optimization. A matrix form of magnetic field at target field positions, G, is obtained. At five target field positions of (0.0, 0.0, 0.0), (0.0, ±2.0, 0.0), (±2.0, 0.0, 0.0) in the rectangular coordinate (unit:cm), target field values are chosen as, 0, 1.0, 1.0, 1.0, 1.0 (unit:Gauss), respectively. From the Biot-Savart law, the z-directional magnetic induction at (x, y, z) from an x-directional current element at (x_0, y_0, z_0) is

$$B_z = \frac{\mu_0 I_x \Delta_x}{4\pi} \cdot \frac{y-y_0}{\left((x-x_0)^2+(y-y_0)^2+(z-z_0)^2\right)^{\frac{3}{2}}} \quad (1)$$

where μ_0 is the permeability of the free space, I_x is the x directional current, and Δ_x is the length of the current element.

(2) The optimal 2-D current distribution is obtained by minimizing the cost $e^2 = i^t i$, where i is a column vector for the current distribution(for both x-and z-directional currents), while satisfying the following two conditions.

(a) $G\ i = l$. This condition is required to set the z-direction field at target field positions to desired magnetic induction values. Here, G is the magnetic field induction at each target field position from each of the current elements as a matrix form and l = [0.0, 1.0, 1.0, 1.0, 1.0]^t.

(b) $\nabla \cdot i = 0$. This condition is required for the current continuity[8]. Both x- and z-directional currents are considered in this constraint. In our simulation, eight outward current elements

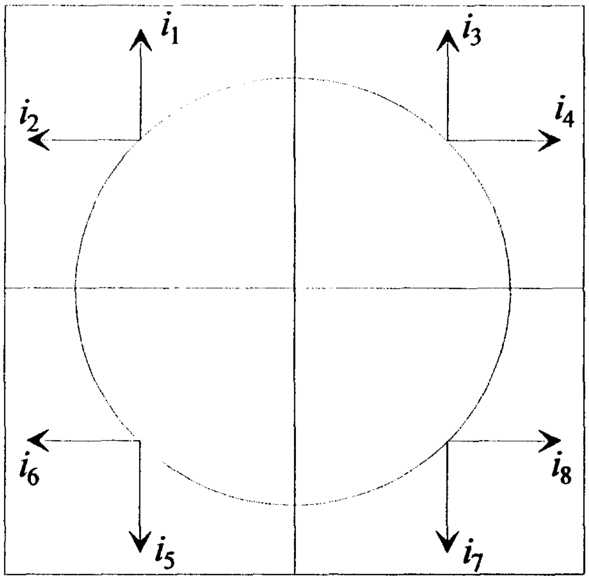


Fig. 2. Eight current elements going out of 4 adjacent locations. The sum of these elements are set to zero for current continuity

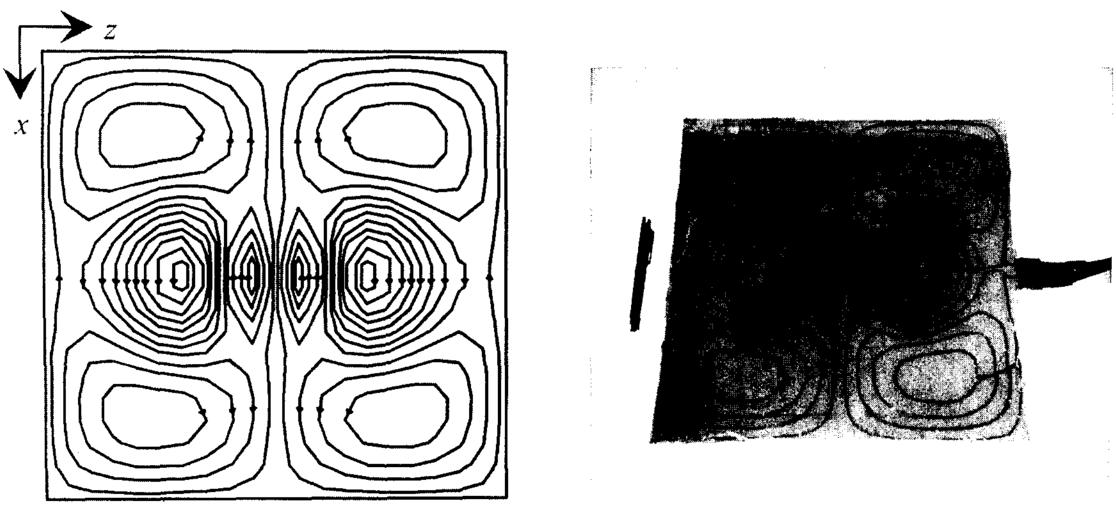
are selected for every set of four adjacent locations as shown in Fig. 2 and the sum of the currents is set to zero.

The above two conditions are combined and written as a matrix form, that is, $Ni = l$. Then the solution becomes

$$i = N^t[NN^t]^{-1}\, l.$$

RESULTS AND DISCUSSION

An r^2 - SGC has been designed by using the proposed design method. The coil has been constructed and used on the 2.0-Tesla MRI system at KAIST. Fig. 3(a) shows the wire layout of an r^2-SGC designed for a size of 40 ㎝ × 40 ㎝ and the assumed coil position is 9㎝ below the imaging center. The specifications of the coil designed by using the target field approach method are as follows: (1) Series resistance (Rs): 0.27Ω (2) Series inductance (Ls): 82.05μH (Measured by using HP 4284A LCR meter with 1V input voltage and 1kHz frequency), and (3) Radial gradient strength : 0.25G/㎠/50A at the center of imaging region. The picture of the constructed coil is shown in Fig. 3(b). From a 50-Ampere cur-



(a) (b)

Fig. 3. The high-order SGC for r^2 gradient generation
(a) The schematics of the SGC showing the wire layout
(b) The photograph of the r^2 SGC constructed according to the wire layout shown in (a). The wire has a 2.0mm-diameter cross-section and epoxy is used to form the coil. To make the field intensity stronger, the wire was wound twice

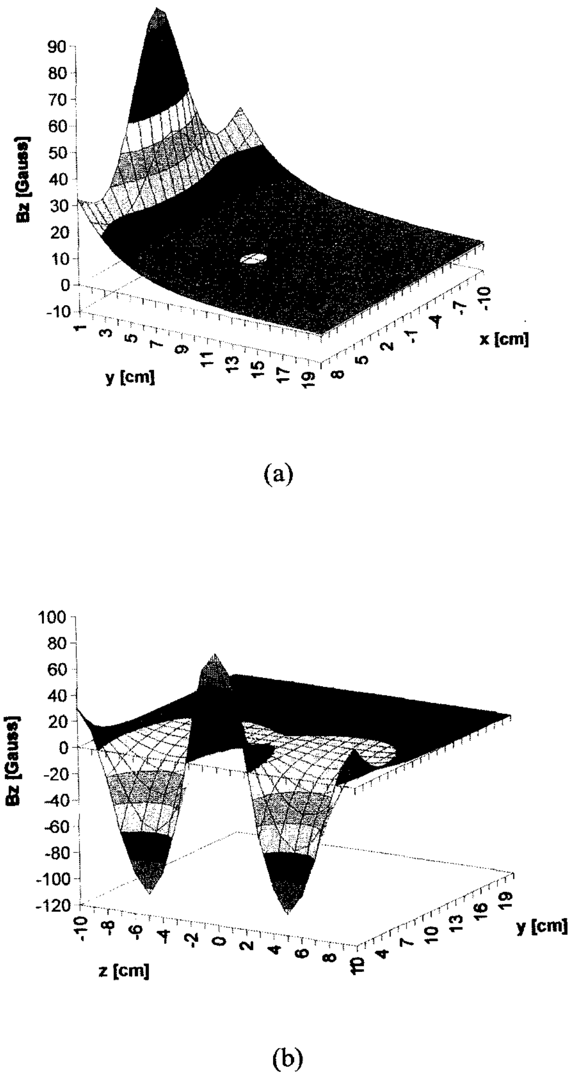


Fig. 4. The z-directional magnetic-field maps calculated from the current distribution in Fig. 3. A current flow of 50 A was assumed for the calculation. The x-y- and y-z-plane field map are shown in (a) and (b), respectively

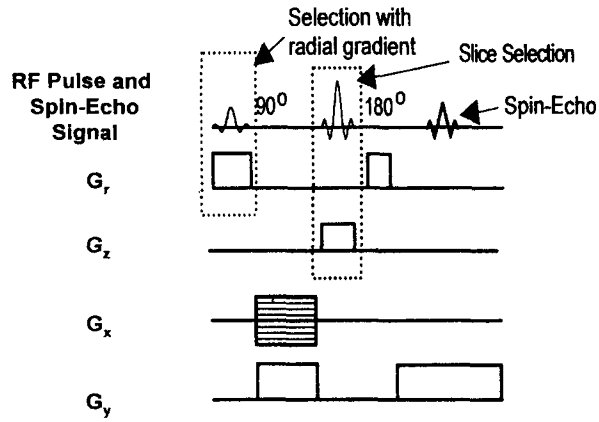


Fig. 5. The RF and gradient pulse sequences for the volume-selective MRI using the proposed high-order SGC. This pulse sequence can be easily changed for spatially selective MRS by removing the spatial encoding and read gradients

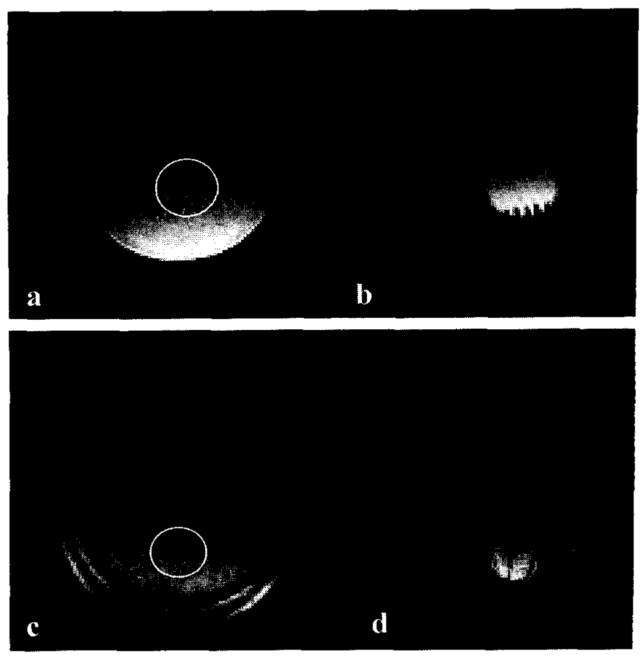


Fig. 6. Phantom (top) and volunteer brain (bottom) images obtained with the proposed localization technique using the r^2 SGC. The selection locations of the images on the right are shown on the left

rent, about a 1-cm-diameter volume can be selected. The z-directional field intensity maps from the wire layout in x-y and y-z planes are shown in Fig. 4(a) and (b), respectively. As expected, an almost-ideal radial field change is seen around y = 9 cm in Fig. 4 (a).

The selection method using the high-order SGC has been tested by implementing for volume selected imaging. The RF and gradient pulse sequences are shown in Fig. 5. Phantom and volunteer head imaging has been performed. As an example, some representative images are shown in Fig. 6. The selection locations of the images on the right are shown on the left. As expected, isolated circular regions are selected.

The above RF and gradient pulse sequences can be easily modified for Localized Magnetic Resonance Spectroscopy (LMRS) or Chemical Shift Imaging (CSI) by removing the read gradient and adding more encoding gradients.

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=국문초록=

이 논문의 목적은 Target field approach방법을 사용하여 2차원적인 공간선택을 할 수 있는 고차 평면 경사 자계코일(High-Order SGC : High-Order Surface Gradient Coil)을 설계하는 것이다. 지금까지 쓰이던 원통형의 고차경사자계코일을 이용한 2차원적 원형 선택방법은 한 개의 RF Pulse로 2차원적인 공간 선택을 할 수 있는 장점이 있었으나 선택되어지는 체적의 지름이 6~8 cm로 너무 크다는 단점이 있었다. 이 논문에서는 이와 같은 단점을 극복하기 위해 영상을 얻고자하는 부분에 코일을 좀 더 가까이 붙일 수 있어서 적은 전력으로 선택되어지는 체적의 지름을 1~4 cm까지 줄일 수 있는 표면 고차자계코일을 Target field approach방법을 이용하여 설계하였으며 Phantom과 인체영상을 통해 제작된 코일의 성능을 확인해 보았다. 이전의 Field component 방법을 이용하여 설계한 코일에 의해서 선택되어지는 체적은 타원에 가까운 모양이 되었으나, Target field approach 방법을 이용하여 설계한 코일에 의해서 선택되어지는 체적은 이상적인 원에 가까운 모양이 되었다.